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The Importance of Project Management in the System Integration, Verification and Validation Process

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Abstract. Suppliers to the oil and gas industry are experiencing an increased pressure from customers to deliver products at a lower cost and shorter schedule. One of the most costly single activity in packaging a Complex System is the process of system integration testing, verification and validation (test phase). In the researched Company this process has also proven to be a bottleneck. Symptoms are accumulated units ready for test, projects that are not put through, and delayed completion of projects.

This paper analyzes the testing process. The initial objective was to identify what impacts the testing schedule. We analyzed the testing process using root cause analysis methods. Our research identified that several issues occurred, both prior to and in the test phase. However, only a few of the issues have a significant impact on the test schedule. This project shows how crucial project management is for complex systems. It also gives an insight to how the company can successfully manage the system integration, verification and validation phase.

Introduction

This paper is a case study from a medium sized Company producing complex systems for the offshore oil and gas industry. The Complex System consist of several subsystems including a starter unit, a control system unit, a main unit etc. The Company does the engineering, project management, planning, component purchasing, quality control and testing of the Complex Systems. The manufacturing and assembly is outsourced to a variety of sub-suppliers. A Complex System takes between one and one-and-a half year from order received to delivery. The cost of a Complex System is in the range of 10-30 million dollars depending on the requirements and features of the system.

The decreased oil barrel price (Rogoff 2016) has led the customers to increase the pressure on suppliers to deliver products at a lower price and shorter project duration. The integration, including testing, verification and validation (International Council on Systems Engineering 2012), is one of the most costly activities, despite the short time duration of around twelve weeks. Furthermore, the integration phase has proven to be a bottleneck, as assembled subsystems waiting to be integrated, verified and validated, accumulate in front of this phase.

Each Complex System is specifically built according to customer requirements. Development and realization of Complex Systems are done by projects. A project can consist of one or several Complex systems. The Company is a partly project based, partly functional matrix-based organization. The project manager and lead discipline engineers are project based, while the rest of the project team is matrix organized.

The Company's facility has two test stands. Here, integration testing, verification and validation of the realized product are performed. The system integration test and verification are done as an internal test without the customer present. Validation is performed afterwards with the customer present. An accepted validation is used as a key milestone for invoicing and is a requirement for delivery. After an accepted validation, the subsystems are disconnected from each other and transported to customer.

As the test phase is the last phase before delivery, a delay in this phase is challenging to mitigate, and can directly impact the delivery date. An impact on the delivery date can have major cost and logistic consequences in form of rescheduling equipment, personnel and transport, and penalties. Accumulation of Complex Systems before the test phase and delays in the test phase can delay the progress in preceding projects and phases.

This is also the focus of this research. The objective was to investigate schedule impacting issues in the test phase at the Company's facilities. We also wanted to know what type of issues these were and how we could improve them. Our research question is:

1. *Within the company, what are the causes of delays in the test phase?*
2. *What methods do the literature suggest to solve these issues?*

We try to answer these questions based on systems engineering methods and tools. To answer the first research question we analyzed the test process. The purpose was to find the causes that impacted the schedule in the test phase. Unfortunately, there was no possibility for an observational research as no Complex Systems were being assembled or tested at the time of the research. Furthermore, little information on the test phase process was documented. This means that our results are mainly based on stakeholder experiences and history with executing the test phase, gathered through interviews and questionnaires of stakeholders.

During the interviews the causes that impacted the schedule were inserted into an Ishikawa cause and effect diagram (Ishikawa 1986) (see Figure 2). When we had exhausted the research for causes, we inserted the root causes from the Ishikawa into a risk priority table (see Figure 5). The main researcher and the test manager rated the frequency, severity and detectability of each root cause (Chrysler LLC, Ford Motor Company, General Motors Corporation 2008; Ambekar, Edlabadkar & Shrouty 2013). From this we calculated the risk priority number. The risk priority number shows which causes are most critical to impact the test schedule.

Our research show that a majority of the causes are related to the work done before the test phase. Specifically the assembly and quality control phase were important. Delays, uncompleted work and components/subsystems that are not adequately tested have a significant impact on the test phase schedule. Our research also shows that a lot of these issues are related to the existing way of planning, the organizational and project strategy.

Some issues relate to the features of the test facility and the design of the Complex System. These issues result in time and resource consuming activities in the test preparation. Another result is that errors are discovered during the system integration testing and verification. The test schedule has not assigned time for troubleshooting or repairs.

Other issues link to lack of procedures, training, communication between the engineering departments and sub-suppliers. This often results in delay and rework in the assembly, quality control and/or test phase.

As our allocated time to this paper was limited, we were not able to suggest solutions to every root cause. To answer the second research question, we therefore focused on what we found to be the main cause. That was the existing project management strategy. We did a literature review on this subject as part of our research.

Based on our literature review we suggest to use Last Planner, Event Chain methodology, Complete Kit concept or Critical Chain project management. We believe that these methods are more suitable and able to handle the Company's type of projects. These project management methods focus on work flow, task readiness, resource planning, mitigation plans and detailed activity planning. Each have different ways of preventing delays, lack of resources, enable mitigations and activity planning.

The preceding section first discusses literature relevant to our first research question, the issues in the test phase, and then moves on to our second research question, project management methods. Then in the following section the case is presented in detail. The paper also has a section on research method. The results and analysis section focus on the first research question. While the discussion section draws lines between the literature review and our findings in the Company. Finally, the paper ends with a brief summary.

Literature Review

Theory on integration and testing in practice. In Muller's book Systems architecting: A business perspective (Muller 2014) the term integration is used for all "activities where decomposed parts are brought together". The goal of integration is described as to "find unforeseen problems as early as possible, in order to solve these problems in time". The book points out that that unforeseen problems can be unforeseen because of limited knowledge. Muller write that in "real-world projects" lifecycle phases overlap each other. "Predictability and stability" and "Flexibility and agility" are two conflicting attributes in integration scheduling. The book state that "the integration process itself turns out to be poorly predictable" and "it does not make sense to formalize the integration heavy, neither to keep it updated in all details". Muller recommend to "use the original integration schedule as kind of reference and to use short cyclic planning steps to guide the integration process."

Tangram: Model-based integration and testing of complex high-tech systems (ed. Tretmans 2007) presents a research project on integration and testing of embedded systems. Their research focus on "model-based test and integration strategies" applied to a real-world project. The Tangram book state that an optimal integration and test plan increases the efficiency of activities, without changing the system quality. Their research demonstrates that "improvements in the integration and testing process are possible by adopting structured, scientifically underpinned, and tool supported methods and techniques". The Tangram book divides methods for reducing test time into 3 categories: making test faster, making test easier and do testing smarter. The Tangram book claim that with model-based integration and testing "a lot of potential problems can be detected earlier, thus cheaper". The Tangram book point out that use of models can significantly reduce the effort in the integration and test process, but the method is a trade-off between the investments and benefits. The Tangram book also researched the link between organizational business drivers and "integration and test strategies".

Theory on Integration, Verification and Validation (Walden et al 2015). Integration process: The Systems Engineering handbook describe the integration process as "to ensure that parts are integrated into the subsystems and that the subsystems are integrated into the system". This regards to procedures, hardware/physical and software parts on both subsystems and systems. The integration process is described as a bottom-up activity. "Interim assembly configurations are verified … to reduce risk and minimize errors and time spent isolating and correcting them". The Systems Engineering handbook suggest keeping the project development team engaged during integration "to assist with configuration issues and redesign". The Systems Engineering handbook also suggest to "define an integration strategy that accounts for the schedule of availability of system elements (including the humans that will use, operate, maintain and sustain the system) and is consistent with fault isolation and diagnosis engineering practices". An output of the integration process is a "completed subsystem or system ready for verification".

Verification process: The verification process confirms that the system, its elements and interfaces are built correctly, i.e. according to requirements. "Verification methods include inspections, analysis, demonstration, test and certification". "Verification activities are determined by the perceived risks, safety and criticality of the element under consideration". The Systems Engineering handbook suggests to not fall for the "temptation to reduce verification activities due to budget or schedule overruns". In addition, they suggest to "avoid conducting verification late in the schedule when there is less time to handle discrepancies, or too early, before the development is complete". The Systems Engineering handbook claims that "a continuous feedback of verification data helps to reduce risk and to surface problems early". Planning of the verification activities "involves choosing the most cost-effective mix of simulations, physical and integrating test results to avoid unnecessary redundancy".

Validation process: The validation process confirms that the system, as built, meets the stakeholders' stated needs. It ensures that this product is the right solution for the customer's problem. "Validation criteria are selected based on the perceived risks, safety and criticality". "Verification and Validation activities often run concurrently and may use different portions of the same environment". The objects to be validated are the designs, prototypes and final systems elements. In addition, the documentation and training materials that describe the system and how to use it is validated in the validation process.

Introduction to literature rev on project management strategies. The following literature review is of management and planning methods in order to answer research question two. The selection of methods is chosen based on their suitability and recognition in projects similar to the Company projects.

Last planner: Barry Papke and Rick Dove has in their paper (Papke & Dove 2013) examined the use of Last planner as a planning and management method for Systems engineering project lifecycles. The Last planner focuses on increased work flow reliability, productivity and changing project management from task flow to work flow view. Last planner also focuses on enforcing a criteria of readiness on tasks. Papke and Dove state that the Last planner uses an Agile process architecture with Lean tools. They find that there are several parallels which make the Last planner suitable for executing projects of complex products. The paper focus heavily on making sure that everything is ready for tasks to be carried out and completed. And to not start on tasks that cannot be completed under the current circumstances. "The Last Planner is an active production control system that actively causes events to conform to plan rather than responding to after-the-fact detection of variance to plan".

Event chain methodology: Lev Virine and Michael Trumper (Virine & Trumper 2017) describe the event chain methodology as "a practical schedule network analysis technique as well as a method of modelling and visualizing of uncertainties". The authors state that "regardless of how well project schedules are developed, some events may occur that will alter it". Event chain methodology focuses on identifying and managing events (risks and uncertainties) before they have an impact on the schedule. To measure the project health Event chain methodology uses the project chance of meeting a set deadline during the lifecycle phases. The foundation of Event chain methodology is defining events that could impact the schedule and how the events would impact. This is done during planning and execution of the project. Event chain methodology uses best-case scenario for defining duration of activities and projects. Virine and Trumper state that "Event chain methodology significantly simplifies the definition and analysis of complex problems associated with project scheduling, such as event correlations or resource levelling." The authors also state that Event chain methodology "allows taking into an account factors, which were not analyzed by other schedule network and analysis techniques". As an end note, Virine and Trumper state that Event chain methodology is able to compare actual project performance to original schedule and constantly improve accuracy of the schedule during a course of a project.

Complete kit concept: The Complete kit concept theory (Ronen 1991) is to never start or perform work (on a design, part, component, subsystem, system etc.) without having all the materials, drawings, procedures etc. ready and available. Boaz Ronen claims that working with incomplete kits will increase work-in-process, lead time, operating expenses, operating complexity and rework. Incomplete kits will also reduce quality, throughput and productivity. Ronen's paper presents the Complete kit concept as an organizational mindset. The complete kit concept is meant for all stages of a project and all departments in the organization. A key element of the complete kit concept is the Gater. The Gater is the person which controls that only complete kits are released and worked on. Ronen suggest implementing the complete kit concept as part of Just-in-time, Theory of constraint or Total quality management methods. The complete kit does not introduce any new theory to the field, but rather a different perspective.

Critical chain project management: Critical chain project management was developed using System thinking and Theory of constraint. With Critical chain project management, resource dependencies and buffers are used to counteract multitasking, student syndrome, rework, inefficiency and delays. In addition, buffers are used to monitor the project health. Larry P. Leach writes in his paper Critical Chain Project Management Improves Project Performance (Leach 1999) that Critical chain project management is "simple compared to other alternative techniques". Leach state Critical chain project management can be implemented "in a short time" without requiring new computer software, although he does not mention any training. In his paper Leach also state that "the critical chain provides the focus for the whole project" while "the buffers provide focus and clear decision criteria for the project manager". Leach concludes in his paper a massive success for all projects that have "diligently applied Critical chain project management".

Case

The Company is a supplier of Complex Systems for the oil and gas industry. The Complex System consist of both hardware and software. The Complex System consists of several supply/circulation systems, manual and system operated valves, pipes, coolers, sensors, hazard detectors and control systems. The system is automatically operated, thus during normal operations there is no human involvement. Personnel is able to take control of the system at any time. The engineering of the Complex System is performed by engineering disciplines such as: controls (software/hardware), electrical, mechanical, project, quality, test, service, analysis and system (process). The project team involves part purchasers, planners, document controllers and other necessary personnel.

The Complex System is developed and realized by the use of projects. Each project usually develops and realize one to four Complex Systems. Each Complex System is specifically built according to customer requirements. The assembly and testing of the Complex System is similar to a mixed-model assembly line. The design and features of the Complex System varies from project to project depending on customer requirements. Design and features of the Complex Systems within the same project can vary. This leads to variations in the integration, verification and validation requirements.

The Company does the engineering, project management, planning, component purchasing, quality control and testing of the Complex System. The manufacturing and assembly is outsourced to a variety of sub-suppliers. The engineering of the main and fuel supply subsystem is done by the Company. The main subsystem consist of several complex components and is the largest and most complex of the subsystems. The assembly of the main subsystem is done by a local sub-supplier. The engineering of the other subsystems is outsourced to local and international sub-suppliers manufacturing and assembling them.

The Company is a partly project based, partly functional matrix-based organization. The project manager and lead discipline engineers are project based, while the rest of the project team is matrix organized. Each project team consist of about ten people. These are project managers, lead discipline engineers, document controllers and other people necessary in a project team. In addition, several resources within the different engineering departments at the Company are involved as needed by the project. Through the engineering and assembly of the product, about 500 to a 1000 people has been involved. This includes both the Company personnel and sub-suppliers.

The Company projects follow the Systems Engineering lifecycle stages, except for the retirement stage. The stages are done in sequence. After the development stage, the assembly is initiated, followed by quality control and testing (Figure 1). When the testing is completed, the Complex System is transported to the customer, commissioned and supported by the Company.

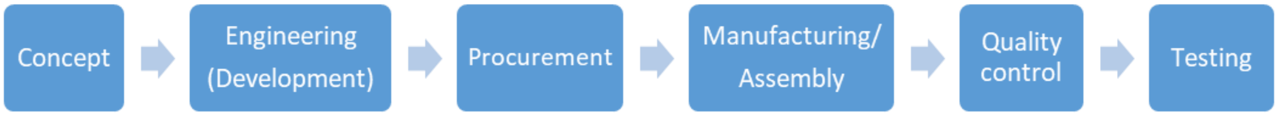

Figure 1. The Company's project lifecycle stages

The test department is very little involved in other phases than test. During bid phase, test department support the bid crew to give a price and feasibility review of test execution. The price and feasibility review is based on the high level requirements from the customer. The test department is not involved again until they start planning the execution of the test, usually a couple of months before the actual test. Controls engineers participating in the test also participate in the engineering of the controls systems. But the controls engineers performing the tests are not necessarily a part of the project team.

The high level design is done during the bid phase with the customer. The length of a project is highly dependent on the complexity of the Complex System, which again depends on the customer requirements. Normally it takes 12-18 months from an order is placed to the Complex System is delivered.

Projects start off with a high level design of the Complex System based on the requirements found during the bid phase. Parts specified during the high level design are ordered as soon as the purchase order is awarded to the Company. The Complex System consists of commercial of the shelf and made to order parts. These are usually purchased in quantities from one to tens. Parts can have anything from weeks to months lead time. Parts are sorted and stored as they arrive, then picked up when needed in assembly.

The detailed design is initiated when the purchase order is awarded and usually continues into the assembly phase. Requirement changes and reluctance from customer to take design decisions can further lengthen the design phase. Parts involved in the detailed design are purchased as the detailed design progresses and freezes.

The assembly phase consists of fabrication of pipes, mounting of parts like valves, sensors, coolers, structural parts, painting etc. Fabrication and assembly activities are often done in conjunction and in parallel. The amount of parts involved and the physical size of the subsystems makes it possible to perform several assembly activities in parallel. On the main subsystem about 20-30 people can work on it at the same time. The other subsystems have fewer people working on it because of their smaller size and complexity. The fabrication and assembly process take from five to twelve months. This depends on the complexity of the Complex System, availability of the parts, design changes, assembly resources and assembly slots. At the Company's facility, up to four Complex Systems can be assembled at the same time.

Quality control of subsystems is done either by the supplier, a third-party inspector, the Company internal inspectors, or all of the mentioned. This depends on previous experience with the supplier, criticality of the subsystem and availability of inspectors. Quality control of subsystems are done at supplier facility. The quality control of subsystems that are made to order goes through a Factory Acceptance Test (FAT). The majority of the subsystems will be tested again during the verification and validation phase as they are required for the Complex System to function as intended. Some subsystems, like the fuel supply, do not go through a FAT before being integrated into the Complex System.

The sub-suppliers perform their own activity planning for the subsystem they are assembling. The Company is informed of the plans and delivery date of each subsystem. The Company is heavily involved in the planning and execution of the assembly of the main and fuel supply subsystem. The assembly plans for the main subsystem is developed with inputs from both the Company and the sub-supplier. The assembly of the main subsystem is also heavily followed up by the Company, having the highest amount of assembly activity hours of all the subsystem.

The Company's facility has two test stands. Here, system integration testing, verification and validation of the Complex System is performed. The two test stands have permanent mounted auxiliary systems and a control room. The auxiliary systems serve functions that will be performed by systems at the customers site and are not within the Company's scope of delivery. The auxiliary systems are cooling water supply, fuel storage and supply, boiler load bank and switch gear. The Company rents in additional resistive load banks for each test to support the boiler load bank. The electricity produced by the Complex Systems during validation is dumped into the load banks, where its transformed into heat. The two test stands share the one control room. The control room holds the control panels and is where the test crew operate and monitor the Complex System during test. Compact version of the Complex System has the subsystems incorporated into a single skid, including the control panels. Other versions of the product have the subsystems on separate skids.

The test stands are equipped with an exhaust system to lead the combustion gases away. An exhaust system is usually a part of the project delivery, but is not used in the Company's integration, verification and validation test. The project specific exhaust system goes through a separate FAT and analyses provided by the supplier.

All subsystems required for the Complex System to function as intended during test and operation needs to be produced by the project. The test activities and sequence are mostly consistent from project to project. The same activities have to be done on each project, but can differ in the way they are done as the design varies. The planning of the test phase is done by the test manager. The resource planning is complex job as there are many different parties involved. The schedule often has to align with availability of resources from sub-suppliers, hired in expert engineers, test crew, project team and customer. In addition, availability of rented in load banks needs to be considered.

Since the test facility consist of two test stands, the test plans need to take into consideration how these are going to be used. Is there two Complex Systems from the same project in the two test stands at the same time, is there two Complex Systems from two different projects and is there Complex Systems being tested right after.

The tests are planned to be carried out on a Complex System that has completed the assembly and quality control phase. There is not scheduled any time for repairs or error searching during the test phase.

The integration test, verification and validation is performed by the test crew. The test crew consists of Company employees from test, controls and field service department. Additional external expert personnel are hired in as required. These are often engineers with expertise on a component, subsystem or test equipment.

The test phase starts with test preparations. This involves moving the Complex System to the test stand, build scaffolding around it for access, calibrating instruments, connecting the subsystems to each other and the auxiliary systems. The integration test is done as a part of the test preparations. The test crew use procedures like yellow lining and loop checking to do the integration test.

Verification is done by pipe pressure test and oil/fuel flushing. This verifies that all pipes, valves, instruments and cables are assembled correctly. After this the system is fired up for the first time, without the customer present. The test crew then go through different test activities and use case scenarios. This is called internal test. The internal test further verifies that the system is assembled correct, that all parts functions as intended and that the system is ready for validation.

The validation is done with the customer present. The validation is performed according to a system test procedure based on customer requirements and regulations. During the system test the Complex System is run through a variety of use case scenarios. The system test also involves testing of the performance of the Complex System, noise and exhaust gas emissions. The system test validates the system as a whole and all the involved subsystems. The test preparations take around eight weeks. The verification takes two to three weeks. The system test takes around a week to complete, depending on the number of use case scenarios involved.

A successful completion of the system test is used as a key milestone and a requirement for delivery. Both the customer and the Company's test crew has to agree that the system test was successful for the test to be completed. After a successful validation the subsystems are disconnected from each other, packaged and transported to the customer' site.

Research Methodology

When we did our research there was no projects being assembled or tested. Without active projects we could not conduct a field observation of the test process. We also looked into documents related to projects and the test phase. But we found that the history of projects was poorly documented and sorted. Only the test execution of last two-three projects was documented in detail. We found it even harder to analyse the history from the assembly and quality control phase. These phases were only documented in occasional minutes of meetings and emails. Finding emails with relevant information was challenging as all emails within the projects are stored in the same folder.

We therefore based our research on interviews with personnel involved in and stakeholders of the test phase. We started interviewing the personnel in the test department to gain knowledge about involved stakeholders and initial issues. We continued with interviews of the involved stakeholders. We did the interviews as semi-structured interviews with open-ended questions. To find the root causes we used the Five whys technique (Murugaiah, Jebaraj Benjamin, Srikamaladevi Marathamuthu & Muthaiyah 2010). As new information emerged, we re-interviewed some stakeholders to verify the new information and gain more knowledge about the root cause. We also interviewed employees working in other phases than test, like assembly, which has the test phase as stakeholder. Simultaneously with the interviews we analysed Minutes of Meetings, test reports, emails and Non Conformance Reports from previously completed projects. No customers were interviewed.

We verified the information from the interviews by comparing them with information from interviews with other stakeholders. We also verified information by reviewing Minutes of Meetings, emails and project documents.

To gain knowledge from project leaders and field service engineers we used questionnaires. One questionnaire was targeted the project leaders and another one was targeted the field service engineers. The questionnaire for the project leaders contained questions relevant for the project leaders to answer. The other questionnaire contained questions relevant for the field service engineers to answer. The questionnaire contained a mix of open- and close-ended questions. We based the questions on knowledge gained from interviews with other stakeholders. We also used the questionnaires to verify information gained from interviews with other stakeholders.

We based the research on experience and information from projects executed after 2010. Changes in the organization, personnel and a new test manager made it nearly impossible to get information from projects pre-2010.

The causes we found were sorted into an Ishikawa cause and effect diagram (Ishikawa 1986) (Figure 2). We used the Ishikawa diagram as a tool for structuring the causes during our research. The Ishikawa could reveal key relations between causes and identify potential factors causing an overall effect. We inserted the root causes into the Ishikawa diagram under six categories. The categories are method, material, equipment, environment, measurement and resource. The six categories are commonly used in Ishikawa diagrams for the manufacturing industry. To identify the root causes we used the Five whys technique. We also used the Ishikawa to present the progress and results, during our research, for the Company management.

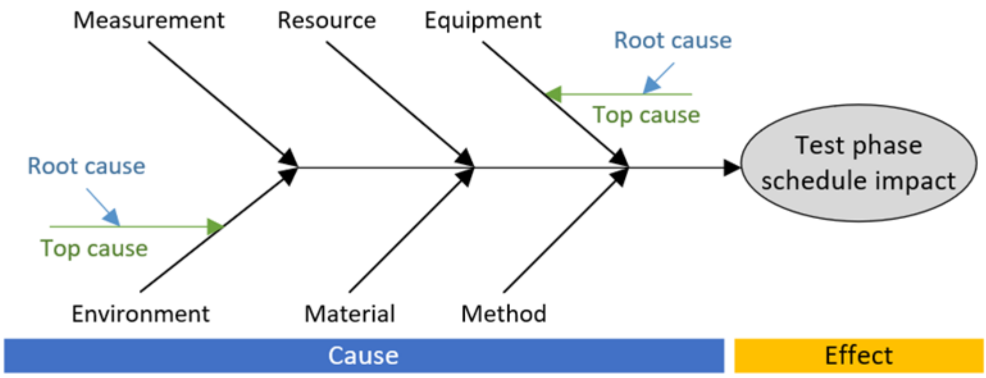

Figure 2. Ishikawa cause and effect diagram

When we completed our research for root causes we inserted the root causes from the Ishikawa into a risk priority table (Figure 5). The risk priority table is based on Failure Mode Effect and Criticality Analysis (FMECA) (Chrysler, Ford, GM 2008; Ambekar, Edlabadkar & Shrouty 2013). Together with the test manager we rated the root causes impact on the test schedule. The risk priority table presents the causes with a Risk priority number rating. The causes were rated in three categories: frequency of cause, severity of cause and how easy it is to detect the cause (detectability). Each cause was rated with a number between 1 and 5 in each category. 1 being low frequency, minimal schedule impact (severity) or easy to detect. 5 being high frequency, high schedule impact (severity) or difficult to detect. By multiplying the number in each category with each other we got the Risk priority number (Severity*Frequency*Detectability = Risk priority number). The lowest possible risk priority number is 1 (1x1x1) and the highest is 125 (5x5x5). The higher the risk priority number, the more likely and critical is the chance of the root cause having an impact on the initial problem. The rating of the root causes is based on the author and test managers experience with the root causes when they occurred. The rating of the detectability is also based on how easily the root cause could be detected with the current procedures, way activities are planned and executed.

At the end we did an informal review of the Ishikawa diagram and the risk priority table to identify if there was an overall cause or connection between the causes. Based on our review of the Ishikawa diagram and risk priority table, we went on to review literature related to what we found the be the link between a majority of the causes. This literature review was to answer research question 2: What methods do the literature suggest to solve these issues?

Results and Analysis

Our research identified a total of 64 root causes. Of the 64 root causes, 29 of them are linked to the Company's project management strategy. These root causes are represented with risk priority number between 4 and 80. A couple of root causes lead to more than one top cause. These are represented under every top cause they are linked to. Since the risk priority number is based on the root cause, these root causes have the same risk priority number.

Figure 3 show the amount of root causes with the assigned risk priority number. The graph shows that 45 root causes of a total 64 have a risk priority number lower than 16. The root causes with risk priority number higher than 16 are mostly spreads evenly between 16 and 36, before taking a leap to risk priority number 45, 60 and 80. This show that there several root causes with minor risk that still affect the test efficiency. Furthermore, it shows that there are a few root causes that present a high risk on the test schedule. The type of root cause (equipment, planning, methods etc.) varies, both on the root causes with a risk priority number higher and lower than 16. Root causes linked to the Company's management, planning and project strategy is represented all over the scale, but is also heavily represented in the higher of risk priority numbers.

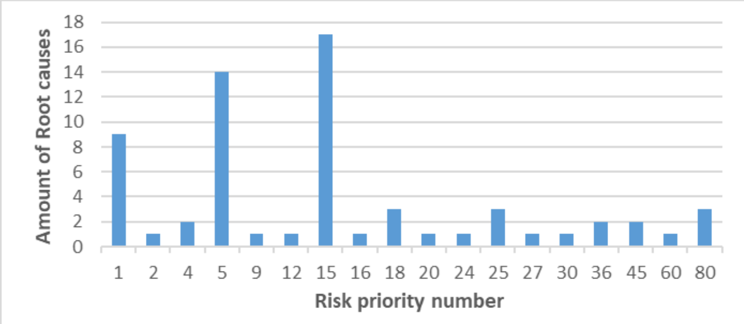

Figure 3. Distribution of Root causes among Risk priority number

Figure 4 show the distribution of root causes among the impact rating in each category. This graph show that a majority of the root causes are easily detectable, with 45 root causes having a rating of 1. The severity of the root causes is more widely spread, but heavily represented from 3 and up. Also the frequency of root causes is heavily represented from 3 and up. This means that although many of the root causes are easily detectable, they frequently occur and can have a considerable impact on test efficiency. The risk priority table (Figure 5) show that there are some root causes which scores high in all three categories.

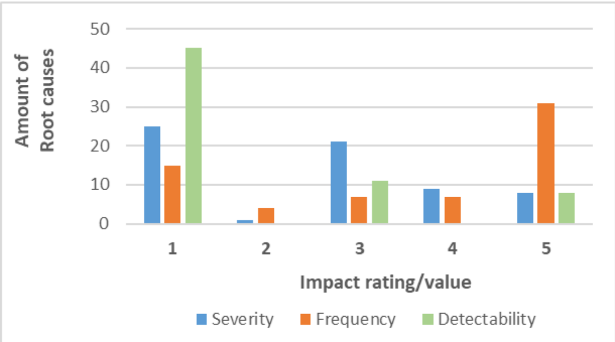

Figure 4. Distribution of Root causes among Rating in each category

During the interviews a frequent comment from several stakeholders was that the Complex system was not ready for test when moved to the test phase. Delays in the assembly phase lead to handing over a Complex System, which still had some assembly work remaining, to quality control and test phase. The research shows that this comes from inadequate activity planning, inadequate resource planning, communication (within and outside the project team), lack of experienced/trained personnel, a culture for accepting that assembly work can be done during test preparations or after a completed test, and that quality control can be limited to save time. There is also a pressure from management to get Complex System moved to test if the product is delayed in the assembly phase. Low level of details in planning of the assembly process and no system for regularly updating the progress makes it challenging to review the health of the project. This often goes at the expense of assembly activities and quality control. This again leads to the Complex System being in three phases at once: assembly, quality control and test. This can lead to assembly work on subsystems that has already been quality controlled and prepared for test. This adds rework for quality control and test crew.

In some cases, the quality control scope is reduced to save time. As the quality control scope is reduced errors usually found in the quality control phase can appear during the test phase. This leads to additional unplanned work. The test schedule is based on a fully assembled and quality controlled

Complex System. There is not scheduled any time for repairs. trouble shooting and repairing during the test phase can take days or weeks depending on the magnitude of the error. Trouble shooting and repairs is especially costly when they have to run the engine to identify the real issue and verify the success of the repair. Trouble shooting and repairing in the test phase means that the Complex System is taking up a test stand.

Often the time assigned to perform testing is reduced as a result of delays in previous phases. The same test completion date is kept and the time is saved up in test phase. The test crew will then work double shift to meet the scheduled test completion date. Changing the test completion date could result in further delays as resource availability varies. Following projects can also be affected. Changing the test completion date can be costly as transportation is done by special trucks and ships, load banks are rented in on a weekly base and penalties kicks in.

Figure 5 shows part of the risk priority table, the six root causes with the highest risk priority numbers. Below we have taken out 13 (including the six in Figure 5) of the root causes with the highest risk priority number and described them in more detail. These root causes have a risk priority number of 25 and higher. We have grouped the 13 root causes into categories of which type of root cause it is. Most of these root causes have a rating above 3 in frequency and severity. Meaning these causes happen frequently and have a high impact on test efficiency. The risk priority number rating of these causes is therefore mostly determined by the detectability. The root cause with the highest risk priority number, of the top 13, have a detectability rating of 5, meaning the issue is very hard to detect. From there it decreases down to 1 as you follow the risk priority number down the table. There is a majority of root causes among the 13 highest risk priority number that can be linked to the management, planning and project strategy.

Risk priority table (Sorted in highest to lowest Risk priority number)						
Alphabetic name	Branch	Description of Root cause	Frequency	Severity	Detect ability	Risk priority number
Cause A	Method	Suppliers quality control, of their own equipment, is not sufficient.	4	4	5	80
Cause B/C	Method/ Resource	Lack of adequate follow up, overview and communication during the assembly phase.	5	4	3	60
Cause D	Resource	Test department is highly dependent on personnell from another department.	5	3	3	45
Cause E	Material	The six engineering departments use at least three different data systems which do not communicate with each other.	4	3	3	36
Cause F	Method	Assembling and integrating the project specific ventilation system takes two resources five weeks.	3	4	3	36

Figure 5. Risk priority table

The following root causes can be connected to the Company's project management strategy.
Cause A: The suppliers quality control, of their own equipment, is not sufficient. This has led to that faults are discovered after the sub-supplier has delivered their product to the Company. At times these faults are discovered as late as the integration or verification stage. This results in unexpected rework to repair the errors and needs to be done by the sub-supplier, the Company or another supplier. This can lead to delays in the assembly phase as the progress is set back and/or assembly work is done during test phase to catch up.

Cause B and C: There is a lack of adequate follow up, overview and communication between the project team and sub-suppliers during the assembly phase. This results in misalignment between scheduled activities and actual progress of activities. This has led to rework of assembly activities, additional activity hours, decreased time to perform tests, assembly errors and lack of available resources to perform the activities. There is also an uncertainty of which assembly activities is actually completed when the package is moved into the test phase.

Cause D: The test department is highly dependent on the crew from the field service engineers to perform the test preparations, integration, verification and validation. The field service engineers main line of work is offshore commissioning and repairs. As a result, the field service department do not prioritize resources to the test phase. The profit for the field service department is higher when doing offshore work for customers, than doing "internal work" for the project such as test activities.

Cause G: There is a culture among the management and the project team that assembly work and quality control can be done during the test preparations. This is done when the assembly and/or quality control is behind schedule. Assembly work and quality control is done during test preparations to try to meet the planned test completion date. Extending test completion date can be costly. Penalties, transportation cost and delay of other following projects are factors that could be affected by the date change.

Cause H: There is a lack of formal training in verification and validation of the Complex System for the field service engineers. The test crew consists of a manager, an assistant manager, three to five persons from controls and three to five persons from field service department. The training for verification and system testing for the field service engineers is done in a "learn by doing" manner. With the extra pressure to complete tests during delays, the unexperienced personnel are looked at as a hurdle instead of an asset. This makes it challenging to train new field service engineers for the verification and validation. In addition, this makes the test phase highly dependent on the field service engineers with adequate experience in verification and validation.

Cause I: The project engineering team is not involved in the test phase. They reside in the offices and attend to other project tasks. The project engineering teams lack of presence and availability during the test phase has caused issues when the test crew have project specific questions or challenges. These questions are mostly forwarded by phone and/or email, but also brought up in meetings. This makes it more challenging for the test crew to communicate with the project team. Lack of answers and information can lead to waiting and/or working without the correct information. Answers to these questions can be critical to the progress and completion of the test phase. Many of these issues regarding the design, function, features, requirements or similar is directed towards the project team as they have made the engineering decisions.

Cause J: This regards to quality control of components. On critical components, the quality control is often done by a discipline engineer from the project team, either by themselves or accompanied by a quality control engineer. This is done in the believe that the discipline engineer has more knowledge about the specific component and is more capable to detect deviations than the quality engineer. Many of these components are multidiscipline, involving mechanical, electrical, system (process) and controls. An electrical engineer could be more focused and knowledgeable in electrical aspect than mechanical, system or controls. An electrical engineer might not have knowledge about the requirements for e.g. paint or fasteners. This can lead to a quality controlled component which does not meet all requirements. Issues that have not been noticed under the initial quality control at the sub-supplier can lead to delays if corrections are needed before the test phase.

Cause K: Penalties for late delivery of projects are frequently used in the oil and gas industry. A percentage of the total purchase order is often used as a penalty when a project is delivered late. This penalty is often claimed for each day or week the project is delayed. The penalty can be costly and in some cases make the project unprofitable within days. The test crew use overtime, double shifts and work weekends to complete the test phase as scheduled when the Complex System enter the test phase later than planned.

The following root causes can be connected to the Company's test facility and/or the product design itself. Cause F: To perform the verification and system test, the test crew use the ventilation and air filter produced within each project. The ventilation and air filter system is delivered in pieces. Assembling and integrating it to the Complex System takes five weeks with two resources. After the system test the ventilation and air filter system is partly or completely disassembled for transport. Without a ventilation and air filter system, particles can enter the engine enclosure and the engine itself. The enclosure is a sealed environment which holds the engine and several sensitive instruments.

Cause L and M: A part of test integration and verification is to verify that the cables from the instrument to the control panel has been connected to the correct terminal and is functioning as intended. This is called Loop checking. Since every instrument on the Complex System is hardwired to the control panel it results in Loop checking of about 200 cables/instruments. Loop checking takes about two weeks with three to four resources. Loop checking is done manually at each instrument, which are placed all over the product. Loop checking is dependent on the instruments being connected by cable to the control panel. This is not done before the product is placed at the test stand. This means that any errors in the instrument, cable or control panel, discovered during Loop checking, are found at a late stage.

The following root cause can be connected to the Company's engineering tools. Cause E: The six different engineering departments use at least three different data systems which do not communicate with each other. This means that changes to the documentation done by one engineering discipline will not automatically be transferred to the other engineering departments. In this specific cause the control panels are designed and assembled according to documentation from the other engineering departments. Changes within this documentation is not automatically communicated to the controls department who are engineering and assembling the control panels. This leads to rework during or after assembly of the control panels. Some changes are not discovered before the integration test or verification.

Discussion

In our research we used root cause analysis methods like Five whys, FMECA and Ishikawa cause and effect diagram to identify root causes that impact the test schedule. We rated the root causes in frequency, severity and detectability to determine the risk priority number of each root cause.

Our analysis of the results shows that the root causes with the highest impact on the test phase schedule, based on risk priority number, are related to: The project management strategy, the test facility and the engineering tools.

The contribution of this paper we consider to be our analysis of the testing process and literature review of mitigation methods. To analyse the test process we used root cause analysis methods like Five whys. Five whys is a recognized technique to find the root cause, especially in in situations where you are dependent on tacit knowledge. We found this to be the correct method of research considering the research questions and circumstances mentioned in this thesis. The results lack accuracy of impact, but from a project lifecycle and management view the results gives a pinpoint on what to consider, expect and how the literature suggests mitigating.

Because of the limited time available to perform the research, we reduced the scope of mitigating the root causes down to one solution. We chose to focus on the group of root causes that had the overall highest impact on the test efficiency. Of the 64 root causes we identified, 29 of them are linked to the Company's project management strategy. The risk priority number of the root causes related to project management strategy spans from 4 to 80. In addition, these root causes are heavily represented among the highest risk priority numbers. In our discussion we will therefore only go into the details of the project management strategy as a mitigation.

Our results indicate that the Company's project management strategy had some challenges with this type of project. The large variety of customer requirements, design and complexity of the Complex System make the choice of project management strategy critical.

To perform the test phase on a Complex System that is not ready to be tested and in shorter time than scheduled seems to be a challenging task. In addition, the test phase is lacking resources, training and procedures. The requirements for continuing to the next phase are compromised and the lines between the phases are diminished as several phases are carried out in parallel. As noted in Muller's paper, System Integration How-To, phases in real life overlap, which is also true for the Company's projects. But the Company project phases are planned in sequence, so the overlap of phases is a result of delay in the phases. In the Company when the phases, activities and progress deviate from the master plan, the completion date is not extended accordingly.

The test facility is in many ways not appropriate for the diverse physical design of the Complex System. The need for modifications on the test structure and assembling the air filter system for every test consumes time and resources.

The accumulation of Complex Systems is caused by delays in the test phase and/or having several projects completing assembly around the same time. The current execution of the test phase will struggle to effectively test Complex Systems in continuous rapid sequence. The configuration and need for modification of the test facility for every project requires additional resources and time. This also concern the assembly of the air filter and ventilation system. The lack of time or buffer assigned to search for errors and perform repairs means testing Complex Systems in rapid sequence increases the risk for delays.

One could argue that the test phase should consider scheduling in time to for trouble shooting and repairs. Even on projects where the product that have been assembled, quality controlled and delivered to test according to plan errors could occur. The systems engineering handbook and the paper System Integration How-To state that issues can occur during the test phase, even though all the previous phases are done correctly. When the test phase has a delayed start, a repair buffer would probably be eaten up by the delay. Or the repair buffer could be thought of as the test phase has "additional time" and don't need to start on time.

Our analysis shows a lack of focus on the test phase during the lifecycle phases preceding the test phase. From a Systems engineering view the test crew should be involved in the concept, development and realization phases. And the project team should be involved in the test phase. The involvement in each other phases is to ensure that there are no issues when the Complex System goes through testing and that testing can be performed as efficient as possible. As the test phase is a representation of the operational conditions and the Complex System performance, involving the test crew in the project team can improve the performance of the Complex System.

Table 1 shows how the reviewed management methods could mitigate the root causes mentioned in section Results and analysis.

Table 1: How management methods could mitigate the researched root causes

Alphabetical name	Description of root cause	Management method	Which features of the management method would mitigate the issue
Cause A	Suppliers quality control, of their own equipment, is not sufficient.	Event chain methodology	Event chain methodology way of accepting that "some events will always come and change/impact the schedule", focus on identifying and managing these events, could mitigate this issue. Usually the suppliers' quality control methods will be reviewed, but there is still possible that issues occur.
		Last planner	The Last planner is an active production control system that actively causes events to conform to plan rather than responding to after-the-fact detection of variance to plan.
		Critical chain project management	The buffers used in Critical chain project management could be used for the additional time this issue demand.
Cause B/C	Lack of adequate follow up, overview and communication during the assembly phase.	Event chain methodology	Event chain methodology is able to compare actual project performance to original schedule and constantly improve accuracy of the schedule during a course of a project.
		Complete kit concept	Complete kit concept is presented as an organizational mindset, which will give everyone in the organization the same understanding of how projects are executed and what is required of each team member. Additionally, Complete kit concept use a Gater which controls that only complete kits are released and worked on.
		Critical chain project management	Critical chain project management use of resource dependencies and buffers to counteract multitasking and project health would give the project management/team a better understand and overview of the project health.
Cause D	Test department is highly dependent on personnel from other departments.	Critical chain project management	Critical chain project management use of resource dependencies would allow the test department to identify available resources. Also, the department who have the resources would have a better overview of resources that are available for the test phase.
		Event chain methodology	The Event chain methodology focus on resource levelling, which could mitigate this issue.
Cause G	Culture for accepting that assembly work and quality control can be done during test preparations.	Last planner	Last planner has a heavy focus on making sure that everything is ready for tasks to be carried out and completed. It also focuses on not starting on tasks that cannot be completed under the current circumstances.
		Event chain methodology	Event chain methodology focuses on identifying and managing events before they have an impact on the schedule.
		Complete kit concept	Complete kit concept is presented as an organizational mindset and focus on never starting or performing tasks without having everything they need to complete the tasks. Additionally, Complete kit concept use a Gater which controls that only complete kits are released and worked on.
Cause H	There is a lack of formal training in verification and validation of the Complex System for the field service engineers	Last planner / Complete kit concept	Both the Last planner and Complete kit concept focus on not starting or performing task without having everything they need to complete the tasks. This includes training. Last planner and Complete kit concept will have necessary training as a requirement to start certain tasks.
Cause I	The project engineering team is not involved in the test phase.	Event chain methodology/ Critical chain project management	Both Event chain methodology and Critical chain project management have a strong focus on resource levelling. This means that they have focus on which personnel is required to each task/phase.
Cause J	Discipline engineers does not have sufficient knowledge of other discipline requirements for components/sub-systems.	Event chain methodology/ Critical chain project management	Both Event chain methodology and Critical chain project management have a strong focus on resource levelling. They realize that the same employee cannot be everywhere and review what kind of personnel is necessary in each task.
Cause K	Penalties for late delivery to the customer makes delivering the project later than planned costly	Last planner	Last planner is an active production control system that actively causes events to conform to plan rather than responding to after-the-fact detection of variance to plan.
		Event chain methodology	Event chain methodology actively measure the project health and takes into account that unexpected events can occur.
		Critical chain project management	Critical chain project management use buffers to monitor project health and mitigate delays.

Both the Last planner and Complete kit concept focuses on task readiness. They acknowledge the challenge of working on tasks that do not have the precondition to be completed at the time they are started. This regards to activities within a phase and the whole phases. This will make sure that the test phase receives a Product that has completed assembly and quality control. This again will lead to carrying out the test phase as scheduled, instead of rushing through.

The Complete kit concept is less complex than the other strategies. Only requiring to implement a Gater into the existing project strategy. This could relatively quickly and easily be implemented into the Company's existing project strategy, without the need for more resources.

The Last planner is a supplementary version of the Complete kit concept. The Complex System projects would benefit from the Last planner focus on work flow, productivity and Lean tools. The Last planner utilises pull production control and focus on always having a steady stream of work ready for resources to carry out. In addition, the Last planner sets out to improve resource utilization, mitigate project variability and predictability of project delivery. These are part of the issues that the Company projects experience.

The Critical chain project management relies on a project buffer. This means that projects can be completed earlier than planned. This could lead to additional cost for storing the completed Product.

The Last planer and Event chain methodology acknowledges that unexpected events can happen during the project execution. The Last planner and Event chain methodology focuses on identifying events schedule and defining mitigating actions before the event can impact the schedule.

The Last planner, Event chain methodology and Critical chain project management all have a method for resource levelling. The test phase would benefit from this as the resources needed to execute the test phase would be dedicated in the plans. In case of unexpected events and delays, these methods have techniques for mitigating this. The Critical chain project management does not incorporate mitigation of unexpected events in the strategy. Instead it relies on the buffers to allow for time and resources to mitigate unexpected events.

Critical chain focuses on the whole system and explain that improvements in a local area might not improve the efficiency of the whole system. Test can at the moment be considered a constraint, but this might move to other phases when execution of previous phases has improved. Since we have not looked into other phases than test we have not been able to locate the constraint of the whole project lifecycle.

The Last planner, Event chain methodology and Critical chain project management all present a high focus on monitoring project health. This enables them to regularly update the progress of the project and initiate mitigations early.

One should not look blindly on the risk priority number. A root cause which score high in "just" one or two categories might be more critical even though the risk priority number is relative low. A root cause which scores high in severity, but low on frequency and detectability might be more critical than a root cause which scores high in frequency and detectability. In addition, root causes which have a lower risk priority number, but leads to several top causes or happen frequently could prove to be more concerning/critical than one with a higher risk priority number.

Quality of research. The information from the interviews are considered to be of good quality. The interview subject was free to talk openly and informed that no sourced would be named in the paper. The subjects were eager to talk about issues and challenges they had encountered. We did not experience that any of the interview subjects spoke disparagingly about the company or other personnel. The information from interviews and questionnaires gave a clear insight to the challenges involved in the test phase.

The results would have benefitted from a better documented history of projects and an extensive analysing of these documents. This would have made it possible to add more accuracy the effect of root causes and their impact on the test phase. The documents would have increased creditability of the results.

Researching the causes of low efficiency during a time of downsizing and lack of new orders was a challenging task. Engineers and sub-suppliers were interested in sharing their experience and views. The leaders and managers were more reluctant towards answering questions, and gave more vague answers. It is not clear to us why they were reluctant to discuss the subject of the paper. It was also more challenging to get the leaders and managers than the others to dedicate time for the interviews and questionnaire.

Only one field service engineer responded to the questionnaire. Hallway discussions with other field service engineers made it clear that they agreed with the answers given by the who one responded. Only one project manager responded to the questionnaire targeted project managers.

Basing the research on interviews and questionnaires was probably the best way to get a wide scope/extent of the causes for low test efficiency. Interviews and questionnaire made it possible to identify issues in several projects at a relative short time. The varying throughput of projects and time needed to perform the test phase means that it could have taken a year or more to get an overview of all the issues by using observational research.

One could argue that the rating of the root causes in the risk priority table should have involved more stakeholders than the test manager and author. But the test manager is the one person with the best overall view of the test phase. The test manager is therefore the one single person who could give a fairly correct image on the impact of all the root causes. The lack of response on questionnaires made this the only reasonable way of doing it, given the time scope.

Some of the root causes identified in this paper cannot be defined as a root cause. The limited time and scope of our research made it challenging to investigate these causes further.

Summary

We analysed the testing process to identify root causes that impact the testing schedule. To analyse the testing process we used root cause analysis methods. We researched the history of projects from 2010 to 2017 and stakeholders experience with the test phase. In total we discovered 64 root causes that increased the time it takes to complete the test phase. We rated the root causes in frequency of impact, severity of impact and detectability. From the rating of the root causes we calculated the risk priority number of each root cause.

The root causes are diverse in type, origin and impact. We identified root causes in areas like configuration of the Complex System, test facility, engineering tools, project management strategy and quality of executed work. The root causes originate from the project phases prior to the test phase and the test phase itself.

Our research shows that the root causes with high impact on test phase schedule, based on risk priority number, are mainly linked to the Company's project management strategy. This leads the Complex System to be in multiple lifecycle phases at the same time which can be critical when the phases are assembly, quality control and test. This further leads to initiating the test phase later than scheduled. Another result is that the test phase is executed on a product that is not ready for the testing, without sufficient personnel and/or training, and on shorter time than originally planned.

Based on our research results and literature review we suggest implementing and utilize a project management strategy like Last planner, Event chain, Complete kit or Critical chain, for the projects entire lifecycle. Implementing and utilizing any of these project management methods will mitigate the majority of the root causes found in our research.

Further work

The causes which require more research to identify the root cause, this paper should be used as a basis for the research. The results of this research can also be used as basis for doing a direct observation of the test phase to add accuracy to the causes impact on the test phase efficiency.

Not all root causes will be mitigated with a different project management strategy. Further work should therefore be to identify and develop solutions to each root cause found in this research.

Further work should look into specifically which project management strategy would be most beneficial for the Company's organization and projects. In addition, how to implement any of the mentioned project management strategies into the Company's organization will need to be researched.

To improve the overall project duration one needs to look at all the lifecycles the projects go through. Further research should be to identify if there are any efficiency issues in the lifecycle phases leading up to the test phase.

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Biography

Christoffer Jimmy Røsegg is employed as a project manager for a Norwegian company supplying to the land based and maritime industry. He holds a bachelor's degree in Mechanical engineering from the University college of Southeast Norway. Christoffer started to study and work with systems engineering in 2013, and has 3 years experience with developing and delivering complex systems to the oil and gas industry. Christoffer has held a variety of functions within projects and has experience with product assembly, quality control, logistics, system integration, verification, validation and management. This paper is the result of the research done for his M.Sc. in Systems Engineering at the University college of Southeast Norway.

Kristin Falk is employed as Associate Professor at University College of Southeast Norway, where she is responsible for the Subsea track and fronting research on systems engineering. Kristin holds a PhD in Petroleum Production and a Master in Industrial Mathematics, both from NTNU. She has worked with research, development and management in the oil and gas industry for 20 years, both with major subsea suppliers and with small start-ups.